Digital Twins for Modeling Replacement Time for CAD/PAD

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ABSTRACT

Naval aviation continues to experience issues with Cartridge Actuated Device/Propellant Actuated Device (CAD/PAD) shortages, obsolescence, lot failures, and delays in production and shipping. Reliability Centered Maintenance (RCM) has proven inadequate for effectively managing the service life of the estimated 2M+ CAD/PAD assets in the existing inventory.

In this paper, we will demonstrate a Sensor-less Digital Twin of two specific CADs and PADs associated with the Navy Aircrew Common Ejection Seat (NACES) that forecasts the remaining useful life of specified devices. This simulation driven analytics toolset could then be utilized to facilitate a seamless transition to CAD/PAD Condition Based Maintenance (CBM) service life management. The specific scope includes the MT29 (Parachute Deployment Rocket Motor) and WB15 (Cartridge Actuated Initiator).

To deliver meaningful projections on CAD/PAD system health, we use a physics-based, stochastic modeling method and follow a proven approach to data collection, validation, creation, and processing. The digital twin solution generates service life predictions by estimating probability distributions of potential outcomes by accounting for random environmental and operational variation over time.

ABOUT THE AUTHORS

Kyle Probst is a Senior Solutions Engineer for Lone Star Analytics. He has been with the company since 2017 and has worked as a DoD contractor since 2001. He specializes in Modeling & Simulation, both continuous and discrete event, and has experience with DoDAF. Kyle provides technical advisement, training and mentoring to the Operational Optimization Solutions department of Lone Star Analysis. Kyle received two degrees from Texas A&M University at Commerce. The first a Bachelor of Science in Computer Information Systems and the second a Master of Science degree in Business Analytics.

David Padula is the Lone Star Analysis Strategic Account manager responsible for building and maintaining strong relationships within the Department of Defense customer base for the delivery of best-in-class descriptive, predictive, and prescriptive analytics. He has been with the Lone Star team since his retirement from the US Navy in April 2019. Having served a 29-year Naval career in both the operational and acquisition community, he brings a wealth of senior leadership experience valuable to the Lone Star Analysis strategic vision. He was raised in San Diego, CA and graduated with a Bachelor of Science degree from the United States Naval Academy. He also has a Master of Science degree from Florida State University and another from the Industrial College of the Armed Forces. He and his wife, Laura, both live in California, MD.

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INTRODUCTION

Problem Statement

Naval aviation continues to experience issues with Cartridge-Actuated Device/Propellant-Actuated Device (CAD/PAD) shortages, obsolescence, lot failures, and production and shipping delays. Reliability Centered Maintenance (RCM) has proven inadequate for effectively managing the service life of the estimated 2M+ CAD/PAD assets in the existing inventory.

According to Naval Air Systems Command (2024),

> PADs include such devices as catapults, rocket catapults, and rocket motors which are used in military aircrew escape systems. All catapults, rocket catapults and rocket motors currently in use are solid-propellant devices. In conjunction with various CADs and other life-support equipment, PADs power the ejection system utilized to eject aircrew members safely from disabled aircraft. Both CADs and PADs contain the energetic material along with a mechanical or electronic actuating component.

Because no ‘as installed’ instrumented health monitoring capability currently exists to indicate performance/useful life, an estimated 70,000 CAD/PAD components are replaced annually to increase the likelihood that these critical safety items will be effective when needed by aircrew. Understandably, conservative service life limits are established to address substantial uncertainty. A by-product of the conservatism is that many of the components removed prior to expiration are done so with significant effective useful life remaining. Safety concerns are also present when components unknowingly reach end-of-life. The MT29 (Parachute Deployment Rocket Motor) has experienced two auto-ignitions. In July of 2007, a CAD/PAD inside a F/A-18D self-actuated while parked outside a hangar at Naval Air Weapons Station (NAWS) China Lake. Another incident occurred in August of 2017 at Naval Air Station (NAS) Lemoore with a F/A-18F. No personnel were near and there were no injuries; however, both aircraft sustained significant damage. (Kraft, Johnson, 2019)

Background

PMA-201 has lifecycle ownership accountability for more than 2,500 different CAD/PAD types with over 380,000 individual components installed on active aircraft. Each component type has unique failure mechanisms that ultimately drives safety, cost, and logistics uncertainty. Recent inadvertent actuations coupled with constraints affecting the health of the CAD/PAD inventory have illuminated the need to approach management of these critical items differently. Existing inventory shortages, obsolescence, lot failures, and production and shipping delays highlight that the current Reliability Centered Maintenance approach is inadequate for effectively managing the service life of these assets.

Stated in DoDI 5000.97 (2023),

> The Department of Defense (DoD) will use digital engineering methodologies, technologies, and practices across the life cycle of defense acquisition programs, systems, and systems of systems to support research, engineering, and management activities. For digital models in particular, programs will identify and maintain model-centric baselines, approaches, and applications in a digital form that integrates the technical data and associated digital artifacts that stakeholders generate throughout the system life cycle. The

program should develop digital model(s) using standard and best practice model representations, methods, and underlying data structures to maximize interoperability.

As such, in August 2018, PMA-201 put Lone Star Analysis on contract to develop a heuristic analytics toolset to facilitate a seamless transition to CAD/PAD Condition Based Maintenance service life management. In January 2021, a direct to phase II Small Business Innovation Research (SBIR) was awarded to take the previously developed toolset and migrate it to a cloud environment.

The vision is to establish a non-intrusive system of automated analysis tools that deliver near real-time performance/useful life projections (by device serial number) and associated maintenance intervention metrics for the entire CAD/PAD inventory. The model will facilitate service life adjustment decisions and support optimized inventory management.

A proof of concept (POC) CAD/PAD digital representations (from here forward referred to as *digital twins*) was developed to bridge the gap between RCM and CBM. According to the digital twin consortium, a digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity (Olcott, Mullen, 2020). Because there are different (and even contradictory) definitions of digital twins, it is important to understand that the CAD/PAD digital twins developed are ‘failure’ twins. The failure twins capture and analyze the accumulation of meaningful stressors for near real time representations of individual components useful life (expended and remaining). The enabling technology has the potential to drive significant cost avoidance/savings and an improved safety posture across the naval enterprise. The POC phase focused on three questions:

- Can a CAD/PAD digital twin be developed that provides accurate measurements and predictions of remaining useful life for target devices?
- Is the current RCM approach to removing and replacing target CAD/PADs on established service life timelines impacting safety and/or readiness?
- Can CAD/PAD digital twin be achieved without adding additional sensors to the aircraft?

For the POC, three CAD/PADs from F/A-18A/C (single seat) Navy Aircrew Common Ejection Seat (NACES) were selected for digital twin development:

- MT29 (Parachute Deployment Rocket Motor)
- MT31 (Under seat Rocket Motor)
- WB15 (Cartridge Actuated Initiator)

As determined by Naval Surface Warfare Center (NSWC) Indian Head Division (IHD), temperature exposure was accepted as the root cause of failure for each of the components. This failure mechanism is largely known and well-understood by the CAD/PAD community; however, prior to embarking on a digital twin POC, insufficient insight into temperature exposure (and resultant effective stabilizer impacts) precluded prescriptive actions. Addressing the gap, digital twin POC models incorporate temperature profile, stabilizer depletion and remaining useful life algorithms to conduct performance/useful life calculations (with consideration to component position in the cockpit, world-wide geographic footprint, platform orientation and time of year/day). Successfully demonstrated POC models have since transitioned to an ongoing model validation and verification phase. Specific POC observations included:

- Digital twins generate results consistent with expectations.
- Digital twins do not require additional aircraft sensor installations.
    - Developed using previously conducted thermal studies, historical weather data, regression analysis, and existing stabilizer depletion equations.
- Analysis suggesting replacing devices at established service life limits introduces a safety risk in some cases and severely under-utilizes effective life (increases cost) in others.
    - Depending on geographic location, analysis indicates stabilizer depletion occurs in as little as 12 months or more than 5 years.
    - Premature removals result in wasted procurement investment and negative impact to Fleet mission readiness.

SOLUTION

Effective Stabilizer

All three in-scope CAD-PAD devices contain Mechanite-19 based propellants and utilize an effective stabilizer to prevent unintended actuations. The stabilizer is measured as a percentage of its overall weight of the propellant. NSWC IHD has mandated that when the effective stabilizer weight falls below 0.2% of the compound's overall propellant weight, the device is no longer safe and should be removed from service. Past failures are not accompanied with exact measurements but indicate values fall below the safety threshold. This, in conjunction with only a handful of past incidents, limits the amount of failure data available and in turn limits which modeling methods are feasible.

NSWC IHD periodically performs Ordnance Assessments where a device is removed from service to have its effective stabilizer measured. Unfortunately, this examination is destructive and is limited to devices out of service. This is where the need for a digital twin becomes important to gauge the status of individual devices, which are not able to be assessed physically, and make decisions accordingly. Operational Assessment Reports (OARs) provide a means to validate the digital twin by comparing its predicted output to the OAR's measurement.

Device Temperature

As discussed earlier, temperature exposure is the driver of device failure. Due to operational constraints, temperature sensors are not authorized for installation on NACES ejection seats so a sensor-less approach must be implemented. A model must be built to estimate the temperature of these devices.

Following an unintended discharge incident, PMA-201 ordered a temperature study to be performed where various mitigation strategies could be tested. A single grounded aircraft, in a hot location, was chosen for the study and sensors were placed inside several areas of the cockpit. The baseline results, where no mitigation was performed, provided a continuous 24-hour period of sensor data along with the outside ambient temperature seen below in Figure 1.

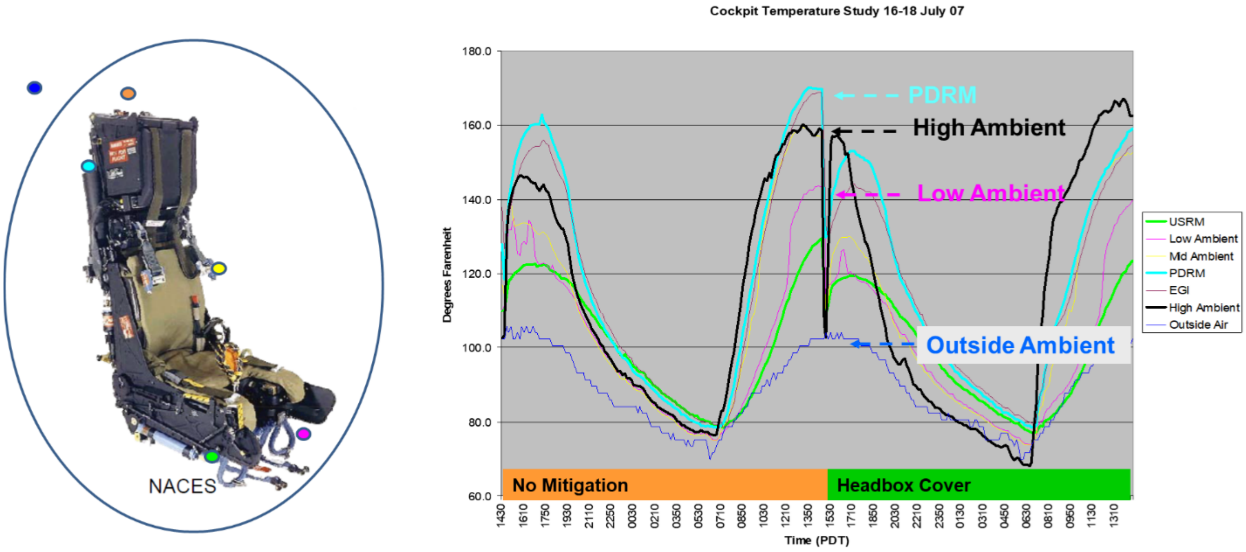


Figure 1. Cockpit Temperature Study (Giblin, Loughran, 2008)

As expected, the results show a rise in temperature following sunrise and a slow decay after sundown. Using this data, a quadratic regression equation was developed to estimate the temperature exposure of the multiple CAD/PAD devices. To achieve the best curve fit, additional independent variables beyond outside ambient temperature would be required; in particular, variables that could explain the sun cycle. Two additional variables were selected. The first variable, solar irradiance, would explain when the sun was shining. The second variable, time since sunset, would explain when the sun was not shining. Neither variable requires sensors but do require some additional information.

To calculate solar irradiance, our model used established mathematical equations provided by Naval Oceanic and Atmospheric Administration (NOAA). The following data inputs are required:

- Latitude, Longitude
- Time Zone
- Date & Time of Day

These equations gave our model the ability to calculate solar irradiance for any location at any date time stamp. Time since sunset is also calculated without sensors by monitoring when solar irradiance returns to a zero value and then begins accumulating time until solar irradiance has a non-zero value.

The end regression equation obtained an adjusted R Square of 0.843. A picture of the curve fit can be seen below in Figure 2. The high estimation at the start of the curve was deemed accurate because during the actual temperature recording, the cockpit canopy would have only been recently closed due to the installation of the sensors and the heat build-up would take a little time.

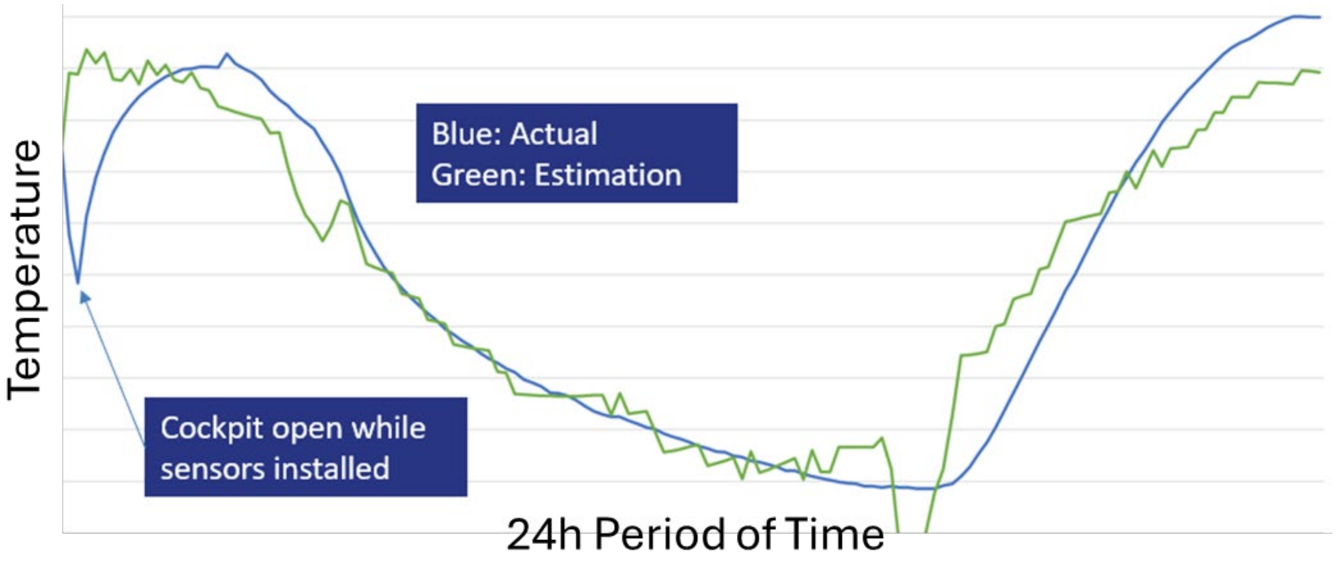


Figure 2. MT29 Curve Fit

A regression equation was developed for each device and a graph of the residuals for all three can be seen below in Figure 3.

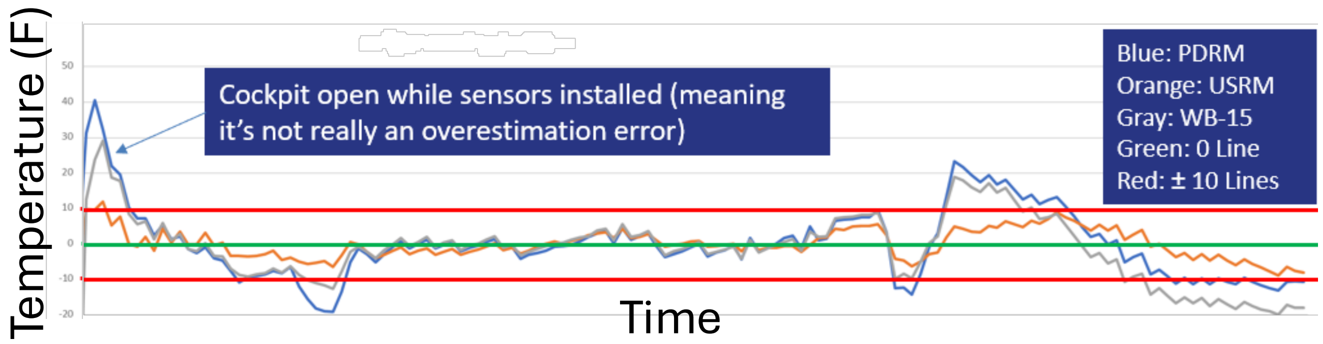


Figure 3. Residuals

Additional rules were implemented in the model as safety guards.

- The estimated temperature will never fall below ambient temperature.
- The estimated temperature will never exceed ambient temperature multiplied by 2.
- The estimated USRM temperature will never exceed PDRM temperature.

Effective Stabilizer Degradation

The next step in the digital twin model, now that an estimated device temperature has been achieved, is to determine the amount of degradation to the effective stabilizer. Using the Arrhenius equation, activation energy is computed using the digital twin's estimated temperature and the reaction rate data on Mechanite-19. Time of exposure is then utilized to calculate energy exposure. The device's cumulative energy exposure is converted to loss of effective stabilizer.

Time Calculations & Aggregations

With the above equations established, the next requirement for the digital twin was implementation of time. Digital twin results are provided in a monthly snapshot. A single representative day is calculated using 24 individual hourly calculations. At the start of each hour, the device temperature is estimated and is assumed to remain steady for one hour. Energy exposure from each hourly calculation is then summed together into a daily energy exposure. This daily exposure is then iterated for the number of days in the subject month. The energy exposure of the month is then added to the cumulative energy exposure of the device.

Useful Remaining Life

Remaining useful life is calculated by subtracting the estimated loss of effective stabilizer from the amount of effective stabilizer when the compound was created. Unfortunately, the amount of stabilizer at creation is not a recorded quantity. There is a minimum requirement for the effective stabilizer weight to be at least 1.8% of the overall propellant weight, but the actual amount varies between lots and is not recorded. The digital twin uses a probability distribution to account for this uncertainty. Subject matter experts at NSWC IHD were consulted during the creation of this distribution.

DIGITAL TWIN DATA SOURCES

Device Installation Data

A U.S. Navy database is utilized to determine which devices are in need of a digital twin. From this database it was determined when the device was installed and which aircraft the device was installed on. The digital twin begins its simulation at the time of installation.

Location Data

A U.S. Navy database is used to determine operational locations of aircraft and, in turn, the location of the devices. A query is executed to determine historical locations from device installation date. If an aircraft has operated from multiple locations in the same month, the location it was in the longest is utilized.

Outside Ambient Temperature

The regression equation that estimates the temperature of the device contains the outside ambient temperature as an independent variable. The digital twin performs hourly calculations for a representative day in each month. To achieve this data, a database of temperature probability distributions was created for each location where a device might be located. Since these devices are used in aircraft, the historic weather at in-scope airports is captured through a NOAA database. Temperatures are pulled for a particular time of day for each day of the subject month, for the past 10 years. These values are used to build probability distributions for each hour of the day for each month of the year. With 24 hourly calculations and 12 months in a year, there are 288 probability distributions for each location.

DIGITAL TWIN RESULTS

Digital Twin Validation

As mentioned earlier, Ordnance Assessment reports can be used to validate the model by comparing the measured amount of stabilizer remaining against a digital twin prediction. Below in figure 4, is a graph of digital twin results with a comparison to the OAR.

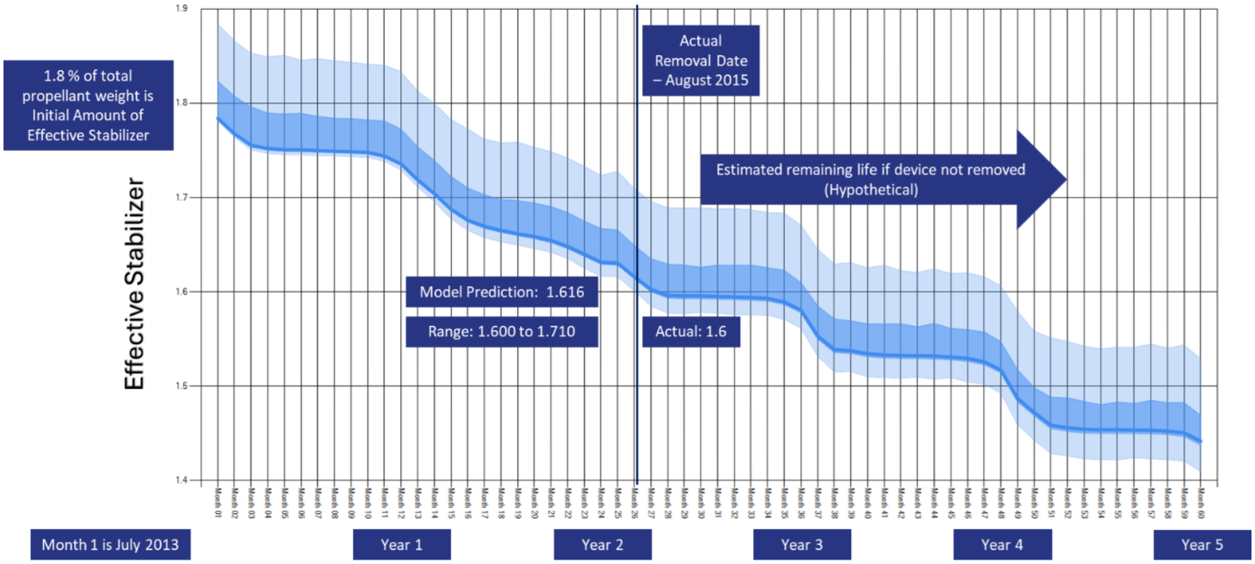


Figure 4. Digital Twin Validation (OAR)

The digital twin utilizes a Monte Carlo simulation to handle the uncertainty from model inputs and because of this, there is a range of values in the result. The blue lines represent the estimated degradation of the effective stabilizer. The dark blue line represents the median or "*most likely*" value. The dark blue shade represents the 30th to 70th percentile or "*likely range*". The light blue shade presents the 10th percentile to 90th percentile or the "*possible range*".

In this case, the device was installed for 26 months, visualized with the dark blue vertical line in the graph. The median result was the effective stabilizer weighing 1.616% of the overall weight of the compound. The actual measured weight from the OAR was 1.6%. Since this is a historic case and we know where the aircraft went after a replacement device was installed, it is possible to estimate what would happen if the original device remained installed. The results show that it could have remained installed for 5 years and still had plenty of life remaining.

Depending on the analyst's risk tolerance, different areas of the distribution can be utilized when making a decision. In this case where the safety of aircrew and airframe are at stake, being risk adverse and utilizing the 10th percentile (lowest edge of the light blue shade) might be the most prudent option.

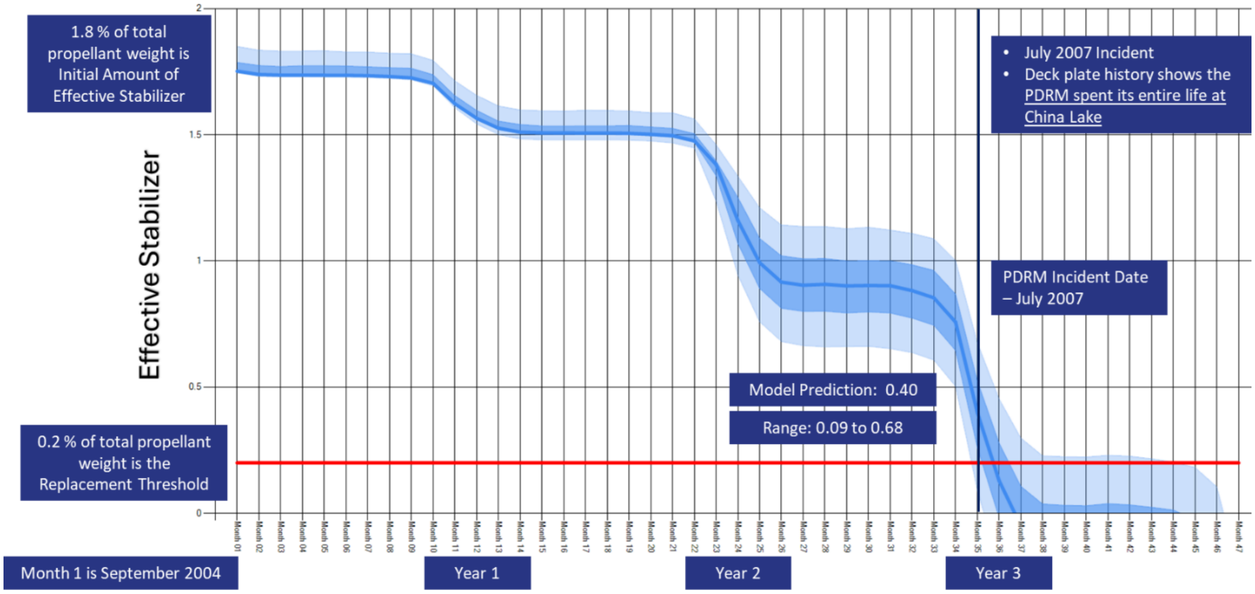
A total of four OARs have been provided thus far for validation. Table 1 shows these results.

Table 1. OAR Comparison to Digital Twin

OAR Measurement	Digital Twin Estimate (Most Likely)	Digital Twin Estimate (Possible)	Installation Duration (months)
1.6%	1.616%	1.600% to 1.710%	26
1.6%	1.600%	1.582% to 1.694%	26

1.8%	1.603%	1.585% to 1.694%	25
1.8%	1.611%	1.593% to 1.706%	25

A fifth validation was run by simulating the aircraft with an unintended initiation back in 2007. Figure 5 shows the timeline of the digital twin results.



1.8 % of total propellant weight is Initial Amount of Effective Stabilizer

- July 2007 Incident
- Deck plate history shows the PDRM spent its entire life at China Lake

PDRM Incident Date – July 2007

Model Prediction: 0.40

Range: 0.09 to 0.68

0.2 % of total propellant weight is the Replacement Threshold

Month 1 is September 2004

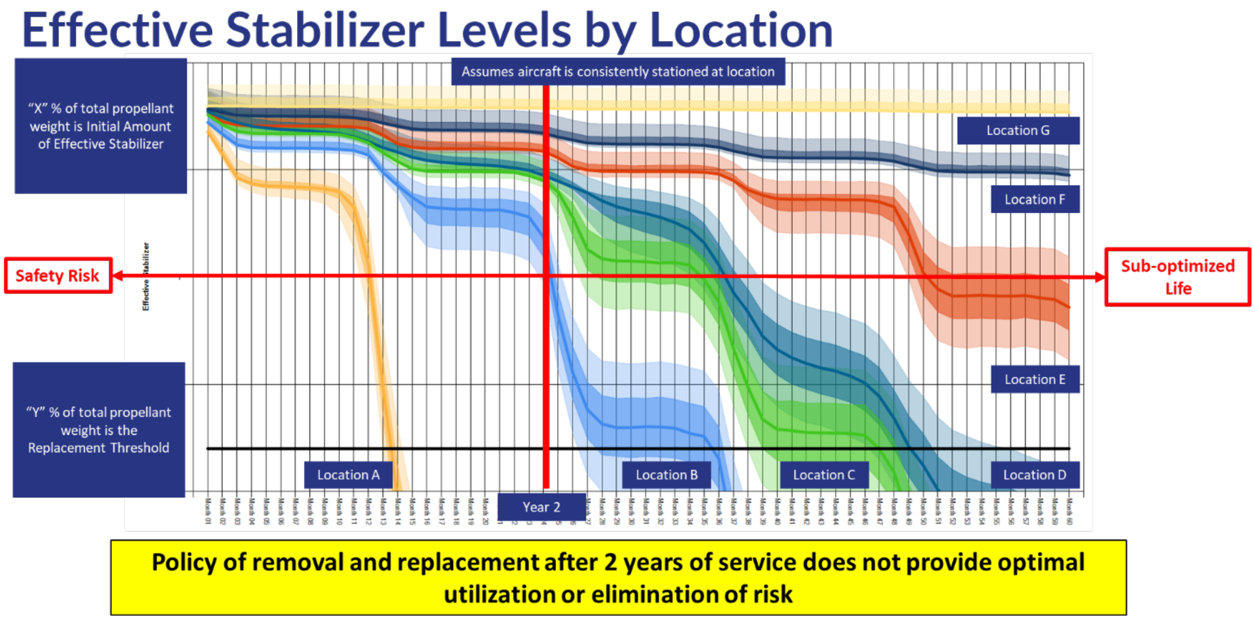
Figure 5. China Lake July 2007 Incident (Digital Twin Estimate)

The incident occurred 35 months after device installation and is represented by a blue vertical line. Digital twin most likely estimate is 0.40% with a possible range of 0.09% to 0.68%. The removal threshold is 0.2% and represented by a red horizontal line. The digital twin results show the possible range falling below the threshold during the incident month and the most likely estimate falling below within the next month.

Doctrine Analysis

NSWC IHD currently operates under a doctrine that removes devices 24 months after installation. When circumstances are met, squadrons can request a service life extension (SLE) to keep the device installed for longer. SLE analysts at NSWC IHD examine these requests on a case-by-case basis and either approve with a new removal date or disapprove, keeping the original removal date.

Using the digital twin, an analysis was conducted showing what the degradation would be like if a device were to spend its entire installed life at a particular location. Figure 6 below shows the results of this 'what-if' analysis.



Effective Stabilizer Levels by Location

Assumes aircraft is consistently stationed at location

"X" % of total propellant weight is Initial Amount of Effective Stabilizer

"Y" % of total propellant weight is the Replacement Threshold

Policy of removal and replacement after 2 years of service does not provide optimal utilization or elimination of risk

Figure 6. Location Analysis

The above chart is divided into two halves with the vertical divider depicting the 24-month removal doctrine. The black horizontal line in the lower part of the graph is the 0.2% removal threshold. If a location's stabilizer depletion estimate crosses the black line on the right side of red vertical, then it represents sub-optimized life (meaning that the device could safely remain installed for a longer period of time). If the intersection occurs on the left side of the red vertical line, this represents a safety risk where unsafe conditions could occur before the 24-month removal period.

As seen in Figure 6, both conditions exist in the displayed locations. A transition from RCM to CBM would both reduce safety risk and maximize effective life.

NEXT STEPS

Development is currently underway to improve the quality of life for NSWC IHD SLE analysts by automating the entry of digital twin input data as well as the evaluation of individual scenarios. Reports deliver the current effective stabilizer estimate for each in-scope device along with a prediction for how far into the future before the removal threshold is met. NSWC IHD is also collecting additional OARs so further model validation can be performed.

ACKNOWLEDGEMENTS

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